An Unusual Example of Pseudoseisms[1] Resulting from Military Exercises[2]

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ABSTRACT: Aerial bombing of the target island of Kahoolawe, Hawaii, during several hours on 19 and 20 December 1961 and on 13 February 1962 generated acoustic disturbances that were felt by people and recorded by seismometers on the island of Hawaii. The azimuth of arrival of the pseudoseisms was calculated from the accurate seismographic responses. Special atmospheric conditions are suspected as prime agencies in the propagation and focusing of these phenomena; lack of specific data in this field, however, leaves the matter of atmospheric structure speculative.

MANY COMMUNITIES have been disturbed by sonic booms created by high-speed aircraft. This problem has not yet become serious on the island of Hawaii, which has only recently established jet facilities. Nonetheless, series of disturbances resembling sonic booms were felt and recorded on Hawaii during several hours of the evening of 19 December 1961, the morning of 20 December 1961, and the evening of 13 February 1962. Since the affected neighborhoods are in a zone of active volcanism, prompt differentiation between artificial and natural events is a problem of immediate concern to the population and to the authorities.

From the results presented here, it seems possible that careful study of the character and timing of sonic disturbances recorded on Hawaiian seismographs by experienced seismologists may permit prompt identification of the source. Other experiments under more controlled conditions have already revealed important facts about energy distribution, refraction paths, etc. between the source and the receptors.

EVENTS LEADING TO THIS STUDY

Between 19:00 and 20:00 (HST) on 19 December 1961, an unusual variety of sensations were both felt and recorded on the island of Hawaii. Personnel of the U. S. Geological Survey's Hawaiian Volcano Observatory at Hawaii Volcanoes National Park, who were at their homes about 3 miles from the observatory, were aware of explosive shocks. When they reached the observatory they inspected the recordings being written by the high-gain, short-period, vertical seismographs at Desert, Uwekahuna, Ahua, and Mauna Loa stations. They recognized that the "pattern" of data as written by the Desert seismograph had been repeated by the Ahua seismograph after a lapse of about 17 seconds. (See Fig. 1 for station locations.) The observatory personnel assumed that these were sonic disturbances, and that they were not seismic events which would have swept the 15-km net in less than 2 seconds. At about the time the shocks were felt in the National Park area they were also felt by residents in the communities of Volcano, Hilo, and Kaumana. Civil Defense officials, alerted by many reports, called the observatory and were advised of the results of the seismogram analysis.

During the evening, all possible local noise sources were checked carefully. Explosive volcanism, though rare at Hawaiian volcanoes, is always a possibility. In this case, the lack of reports from Kona seemed to rule out eruption of the dormant volcano Hualalai. A radio check with personnel at the U. S. Weather Bureau, Mauna Loa Slope Observatory, 6 miles from the summit caldera of Mauna Loa, indicated that no one there had felt, heard, or sensed the dis-

[1] This term is used in Gutenberg and Richter's published description (1931) of a similar incident.

[2] Publication authorized by the Director, U. S. Geological Survey.

[3] U. S. Geological Survey, Flagstaff, Arizona, Denver, Colorado, and Hawaiian Volcano Observatory, Hawaii, respectively.

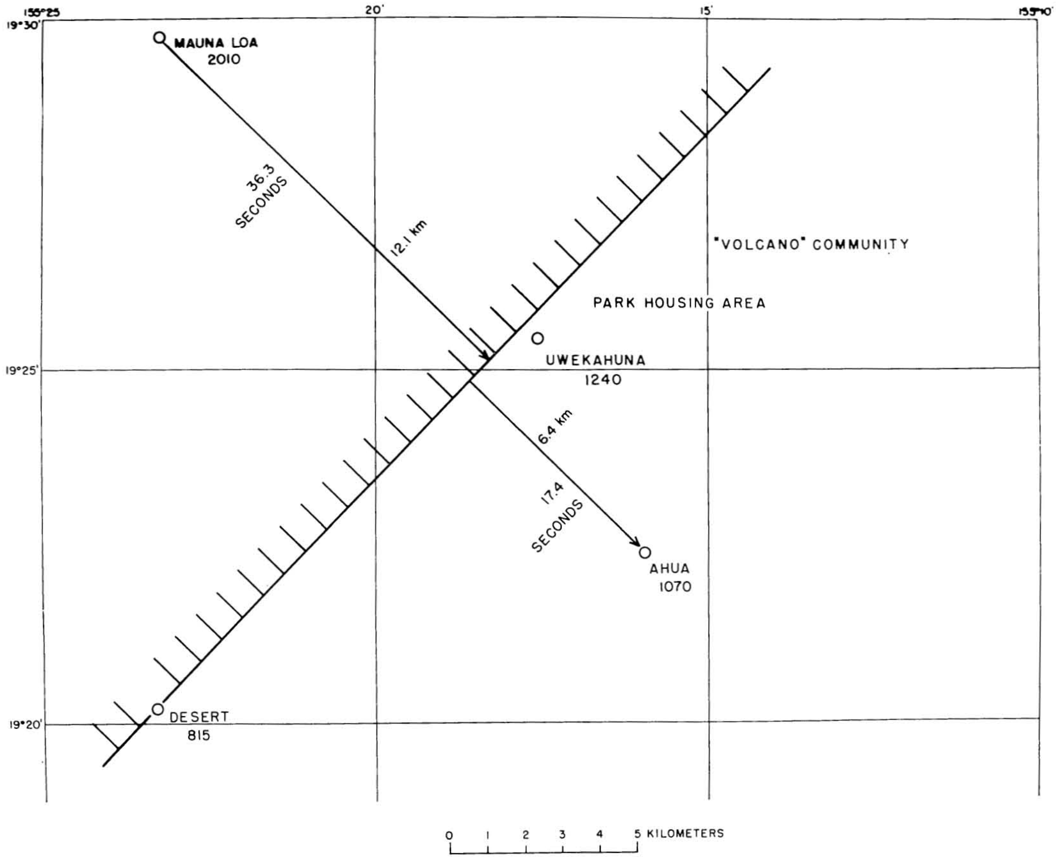

FIG. 1. Locations and elevations, in meters, of U. S. Geological Survey seismometers (*circles*) on Kilauea and a constructed sonic wave front based on data picked up by the seismometers.

turbances, thus eliminating Mauna Loa as a source. Gunfire from the U. S. Army base at Pohakuloa, which is often heard by Hilo and Volcano residents during training exercises, was ruled out as a possible cause when it was learned that the base was then inactive.

INTERPRETATION OF RECORDED DATA

All four seismometers are timed from the same master clock, and accurate comparison of events recorded by these instruments is possible. Figure 2, a copy of the Desert seismogram, shows the disturbances described above, as well as those of a few local earthquakes for comparison. As the Desert seismometer seemed to be most sensitive to the sonic arrivals, its record was used in compiling a master list, which includes every suspicious event recorded during the disturbed period. The Uwekahuna seismograph has a response similar to that of the Desert, although it is recorded optically. All events on the Uwekahuna record are shown in Table 1. Records from the Mauna Loa and Ahua instruments are similar to those from Desert. As stated above, events recorded on Desert were recorded on Ahua 17 seconds later.

The next morning, 20 December 1961, observatory personnel noticed renewed activity on the Desert record. People in the Hilo area, who perhaps were alerted by the events of the previous evening, called the observatory, and, as was the case the evening before, reported that they had experienced an audible sensation rather than a physical one, and that windows vibrated strongly and wall clocks shook. With the expectation that Mauna Loa should be the first local station to record these events, the gain on that

TABLE 1

ARRIVAL TIMES AT SUMMIT STATIONS OF SONIC DISTURBANCES FROM THE EVENTS OF 19 DECEMBER 1961
(Numbers in parentheses are recorded double-amplitudes, in millimeters)

DESERT	UWEKAHUNA	AHUA	MAUNA LOA
18-29-06.3(3)			
29-35.3(3)			
31-37.2(6)			
31-42.8(14)			
35-42.8(4)			
39-54.3(12)	54.6(5/2)	40-11.6(5)	18.1(5)
40-36.9(7)			
40-39.8(10)			
40-58.3(34)	59.1(4)	41-16.0(14)	22.1(5/2)
43-16.8(23)	17.5(3)	34.5(21)	
43-46.7(38)	47.5(2)	44-04.6(16)	
44-24.8(19)	26.3(1)	42.5(4)	
44-56.3(21)	57.0(2)	45-14.1(6)	
47-32.8(8)	33.5(5/2)		
47-56.9(7)	57.8(4)	48-14.5(2)	
48-28.8(47)	30.0(8)	45.6(7)	47-53.2(2)
48-49.5(21)	50.1(2)	49-06.9(2)	
51-41.5(5)	42.0(5/2)	58.7(5)	
52-07.5(14)	08.0(3)	24.9(6)	51-31.5(1)
52-40.6(10)	41.4(2)		04.9(3/2)
55-48.1(11)	48.6(5/2)	56-05.4(3)	12.0(5)
56-21.0(4)	21.5(4)	38.3(4)	55-45.0(5/2)
56-46.3(5)	46.7(4)	57-03.6(5/2)	10.1(3/2)
59-09.2(2)			
59-48.5(5)	49.4(7/2)	00-07.5(3)	
19-26-42.1(10)	40.6(4)	57.6(8)	
27-14.1(18)	16.3(2)	31.5(5/2)	
27-49.5(27)	49.5(5)	28-06.4(8)	
30-57.0(2)			
31-40.3(5)	40.6(4)	55.6(1)	
32-37.4(12)	37.7(6)	53.0(3/2)	04.0(2)
35-14.0(5)	16.3(3/2)	33.7(2)	
36-08.1(5)	07.2(2)	25.7(3)	35-31.8(2)
36-58.5(3)			
38-56.1(10)	56.4(4)	39-13.4(5)	
39-51.0(22)	50.5(5)	40-08.5(11)	39-15.2(3/4)
41-01.1(19)	01.2(6)	18.6(5)	
48-53.8(3/2)			
20-34-35.8(2)	48.6(1)		

amplifier was increased greatly. The gain on the Ahua amplifier was also increased. The data listed in Table 2 generally bear out the observations suggested by Table 1. In Figure 3 are shown other locations at which there are instruments similar to that at Uwekahuna. It is interesting that such instruments on Maui and at Kamuela, Naalehu, Hilo, and Pahoa on Hawaii all failed to record these events. Furthermore, residents and police at these places, as well as along the west and northeast coasts of Hawaii, who were questioned later, reported no unusual sensations.

On 13 February 1962, 15 additional events were recorded. The observatory had been alerted to expect these events; and so, *while they were recording,* the staff phoned about six of the Hilo residents who had reported alarming sensations during the morning of 20 December 1961. Of those called, only one thought that a similar event had just taken place, although no concern or alarm was engendered. This third

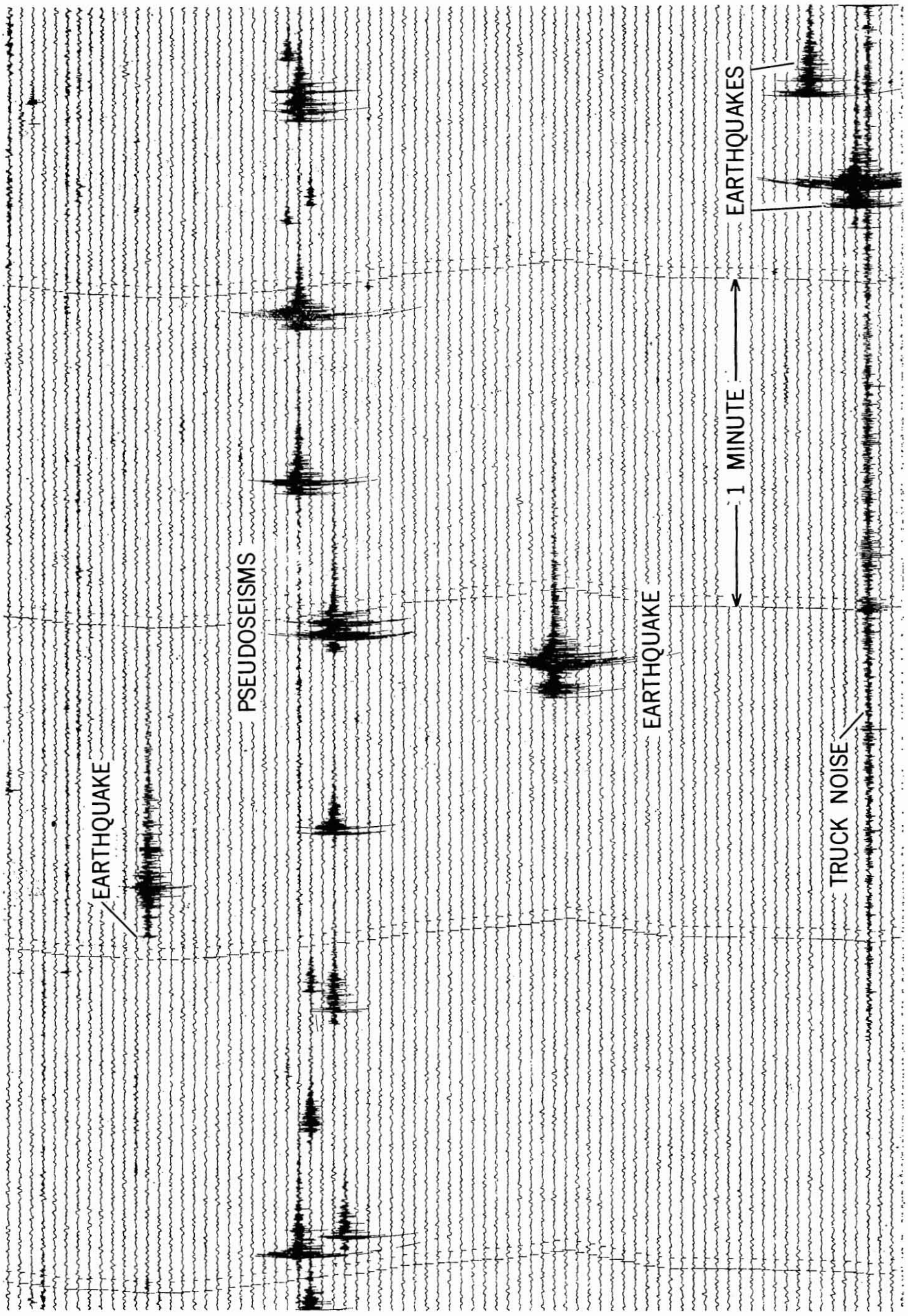

FIG. 2. Copy of original Desert seismogram showing events described in text.

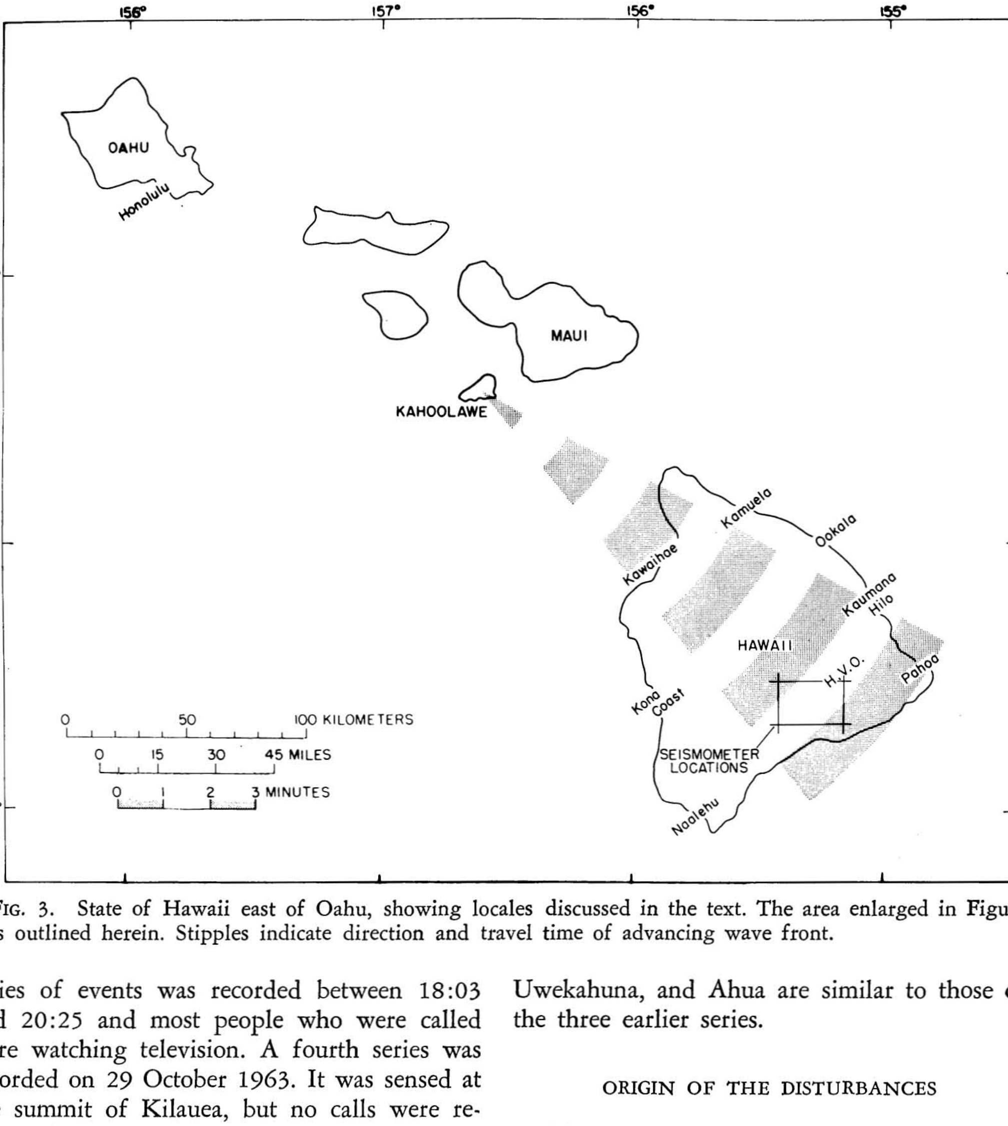

FIG. 3. State of Hawaii east of Oahu, showing locales discussed in the text. The area enlarged in Figure 1 is outlined herein. Stipples indicate direction and travel time of advancing wave front.

series of events was recorded between 18:03 and 20:25 and most people who were called were watching television. A fourth series was recorded on 29 October 1963. It was sensed at the summit of Kilauea, but no calls were received from other places.

The third and fourth series of events presented a picture quite like the first two and have been only summarized in this presentation. Average differences between arrival times at Mauna Loa and at each of the other stations, for each of the four series of disturbances, are presented in Table 3.

The fourth column of Table 3 corresponds to the fourth series (of five events) which was confirmed to be sonic in nature but was not recorded at Mauna Loa. Relative arrival times of the 29 October 1963 series at Desert, Uwekahuna, and Ahua are similar to those of the three earlier series.

ORIGIN OF THE DISTURBANCES

After the first series of disturbances on 19 and 20 December 1961, it was ascertained that Navy bombing exercises had been conducted during the suspect time-intervals. The target islands Kahoolawe and Kaula Rock had been "dive bombed" by aircraft from the carrier USS "Coral Sea," using 500- and 1,000-lb bombs which exploded on contact (rather than above or within the ground). Figure 3 shows the Hawaiian Islands east of Oahu and indicates sectors of airspace traversed during successive 1-minute intervals by sonic wave fronts which originated at Kahoolawe. The region on Hawaii

TABLE 2

MATCHED ARRIVAL TIMES AT SUMMIT STATIONS OF THE EVENTS OF 20 DECEMBER 1961
(Numbers in parentheses are recorded double-amplitudes, in millimeters)

DESERT	UWEKAHUNA	AHUA	MAUNA LOA
09-56-42.5(21)	43.7(4)	57-00.9(5)	06.5(5/2)
10-26-56.6(14)	56.2(4)	27-12.9(6)	19.3(3/2)
27-15.5(3)			
27-45.0(13)	45.0(4)	28-02.0(4)	08.0(2)
29-18.8(24)	19.5(4)	36.2(3)	28-42.8(1)
30-03.0(3/2)			
30-48.9(14)	51.0(5)	31-08.0(3)	14.5(2)
31-52.0(5)	52.0(2)		
11-11-07.3(6)	07.5(4)	27.5(3)	10-29.5(1)
40-54.7(12)	56.0(6)	41-12.0(1)	16.8(1)
41-23.3(17)	23.0(7)	41-40.5(1)	40-46.3(3/2)
41-44.8(17)	44.1(6)	42-02.3(2)	07.0(3)
42-12.9(16)	13.1(3)	30.7(3)	36.3(2)
47-40.6(5)	41.6(4)	57.9(2)	04.6(5/2)
48-40.9(20)	41.5(2)	59.1(1)	04.8(1)
49-04.2(16)	05.1(7)	21.3(2)	
49-33.0(12)	34.6(11)	51.6(7)	48-57.6(2)
53-27.5(11)	27.8(2)		
54-19.0(15)	19.5(4)	36.4(3)	53-42.9(3)
54-38.2(10)	38.6(2)	55.9(1)	01.8(1)
55-12.0(4)			
59-52.8(9)			
12-00-45.8(20)		01-03.5(6)	09.5(1)
01-12.0(14)			00-36.1(1/2)
06-31.0(11)	31.2(2)	49.5(2)	05-53.0(3/2)
07-28.0(5)		46.3(1)	
07-32.2(4)			
08-02.5(4)			
11-44.5(21)	45.0(3)	12-03.0(5)	08.8(3)
12-44.4(20)		13-02.5(1)	08.6(3/2)
19-40.8(23)	41.8(8)	58.9(19)	04.7(3/2)
27-54.3(17)	52.2(2)	58-10.0(3)	16.2(3)
59-26.0(14)	26.7(3)	43.8(8)	58-49.6(5)
13-01-12.5(18)	13.7(9)	30.7(9)	00-36.6(4)
04-27.7(18)	28.7(7)	45.9(2)	03-51.7(2)
05-46.5(31)	47.5(6)	06-04.2(4)	10.1(6)
06-42.7(13)	43.1(3)	07-00.6(2)	06.3(1)
11-17.6(21)	18.6(6)	35.8(6)	10-41.2(4)
12-02.9(15)	03.8(3/2)	21.1(5/2)	11-26.6(7)
13-03.6(9)	04.6(2)	21.5(1)	12-27.5(3)

TABLE 3

TIME OF ARRIVAL OF SONIC WAVE FRONTS AT EACH STATION COMPARED WITH ARRIVAL AT MAUNA LOA, FOR EACH OF FOUR DIFFERENT BOMBING DATES

STATION	ORDER OF ARRIVAL	19 DEC. 1961	20 DEC. 1961	13 FEB. 1962	29 OCT. 1963
Mauna Loa	(1st)	0	0	0	not recorded
Desert	(2nd)	+35.9 sec	+36.4 sec	+36.6 sec	"+36.3 sec" (assumed)
Uwekahuna	(3rd)	+ 0.7 sec	+ 0.6 sec	+ 0.2 sec	— 0.2 sec
Ahua	(4th)	+16.9 sec	+17.2 sec	+16.7 sec	+16.7 sec

in which the disturbances were recorded and felt is approximately 190 km from the Kahoolawe source. Kaula Rock is 400 km to the west of Kahoolawe. An approximate schedule supplied by the Navy did not specify the exact time of any individual explosion or the total number of bombs dropped. By virtue of overlap in attack periods on the two islands, however, there is weak evidence, based on schedules of exercises for 19 and 20 December 1961, that all disturbances recorded and felt on the island of Hawaii originated at the closer target, Kahoolawe. On 13 February 1962, both targets were bombed simultaneously, but because the bombing log is skeletal, no conclusions can be drawn. No log was provided for the exercise of 29 October 1963; but it was confirmed that bombing had taken place and it was implied that only Kahoolawe was involved.

Bombing exercises on these targets during 1961 only, and qualitative results from them obtained by searching the seismograms follow:

DATE	HOURS	RESULTS
24 Feb.	06:40–14:30	No recordings, eruption tremor in progress. No sensations reported.
16 May	05:30–13:00	Neither recordings nor sensations.
22 Aug.	05:00–12:00	Same as above.
	15:30–20:00	Same as above.
23 Aug.	09:35–13:30	Same as above.
18 Nov.	05:40–13:10	Weakly recorded on Ahua only, no sensations reported.
20 Nov.	10:30–13:40	Neither recordings nor sensations.
	17:45–19:20	Weakly recorded on Ahua only, no sensations.
21 Nov.	09:30–13:35	Very weak on Mauna Loa and Ahua only, no "felt" reports.
19 Dec.	06:30–12:30	Weakly recorded, no sensations reported.
	17:45–20:00	Many reports and good records (Table 1).
20 Dec.	09:30–13:00	Some reports and good records (Table 2).

GRAPHICAL ANALYSIS: FIGURE 1

Because of the almost simultaneous arrival of the sonic waves at Uwekahuna and Desert, it was convenient to use a graphical technique to estimate the azimuth to the source on the basis of data summarized in Table 3. On Figure 1, therefore, an assumed wave front has been drawn at the instant it passes Desert seismometer. The seismic stations which time such wave fronts are arrayed along a chord which is approximately 20 km long and about 20 km from the source. With this geometry, the chord is within 0.3 km of the circular segment it intersects; therefore, straight-line wave fronts have been assumed.

Seismograph recordings of sonic disturbances differ considerably from those of local earthquakes. There are no definite phase identifications for sonic arrivals as recorded by short-period seismometers; instead, the maxima have been read on each record. Some events were recorded as featureless bursts barely resolvable above the normal background noise. The Desert record as illustrated in Figure 2 usually gave the clearest and largest arrival. We can only speculate on the possible interference of wave groups following slightly different paths from the source to the receivers and on the effect such interference would have on the times of maxima at different receivers. However, the relatively low velocity of sound in air reduces the degree of precision necessary in timing sonic arrivals compared with that for seismic waves, for example.

If we assume that the correlation of the sonic arrival between receivers was in error by 5 or 10 seconds, and if we apply all of this error at either extreme of the hypothetical 20-km recording chord, errors of only 1° of arc would result. These errors are so small that confusing a source on Kahoolawe with one on Kaula Rock seems unlikely.

If we make these simplifications and allowances for error, and if we assume further that constant velocity prevailed in the seismic recording zone and over the 200-km propagation path, a direction of N 44°–46° W may be read from the diagram on Figure 1. This solution is excellent for a Kahoolawe source. (The Kaula Rock target is about N 64° W of the seismic pickup location.)

VARIATIONS IN APPARENT VELOCITY

The traveltimes (averaged from Table 3) for each leg in the wave front's passage are shown in Figure 1. The spacing provided by existing instrument locations indicates two distinct travel paths: the high elevation path, from Mauna Loa to Desert/Uwekahuna, and the lower elevation path, from Desert/Uwekahuna to Ahua. Apparent velocity for the high elevation path is 0.33 km/sec, which, on the basis of the slope distance of 12.6 km, results in a ground velocity of 0.35 km/sec. These results are consistent with sonic velocities in air (Chemical Rubber Publishing Co., 1947:1928) of 0.33 km/sec at 0° C, and 0.34 km/sec at 20° C. Similarly, the lower elevation wave front path yields an apparent velocity of 0.37 km/sec, a condition observed at ambient temperatures of about 70° C.

Blumenstock (1961) summarized weather data collected in Hawaii and concluded that the winter mean temperature was 20° at the National Park housing area (see Figure 1) and that it decreased 2° for every 1,000 ft of elevation. He observed the remarkably "equable temperature conditions" in Hawaii—that is, the small range between winter and summer means at any one observation point—but he also stressed the great variations in temperature and in rainfall caused by very local topographic situations.

Additional, near-surface temperature variables which may bear on our present problem are the diurnal temperature and wind-direction patterns. In table 3, the 19 and 20 December 1961 figures represent average traveltimes for a large number of events in each of two groups. The 19 December events occurred at night; the 20 December events occurred during the daytime. The apparent velocities which occurred in the two events are:

(1) Mauna Loa to Desert (12.6 km slope distance): 35.9 sec, or 0.351 km/sec for the evening events; 36.4 sec, or 0.347 km/sec for the daytime events.

(2) Desert to Ahua (6.4 km distance): 17.6 sec, or 0.364 km/sec for the evening events; 17.8 sec, or 0.360 km/sec for the daytime events.

As shown above, the gross velocity increases as the sound front moves from the slopes of Mauna Loa to the flatter terrain at the summit and flank of Kilauea, and the velocities are systematically lower in the daytime than at night. At one atmosphere pressure, the velocity of sound in air increases 0.012 km/sec between 0° C and 20° C. Therefore, the natural expectation would be the reverse of our findings, i.e., velocities expectedly would be slightly greater during the daytime than during the evening, when temperatures are lower. Again, Blumenstock's findings (1961:6) can be invoked for a mechanism which might explain this seeming contradiction: "The usual regime is to have upslope winds by day and downslope winds by night." In our situation downslope winds (nighttime) would augment velocities across our recording range; upslope winds (daytime) would provide relative decreases in apparent velocities. The velocity increase we seek to explain by this mechanism is 4 m/sec or about 8 miles/hr—a modest windspeed vector which is not unrealistic.

Thus, some of the diurnal changes in sonic traveltime shown in Table 3 can be explained by assumptions of expectable change due to diurnal wind-velocity conditions. However, such changes can be only partially responsible for the difference between apparent velocity over the Mauna Loa-to-Desert leg and that over the Desert-to-Ahua leg. As we have pointed out, such an assumption would require an unrealistic ambient temperature of 70° C for the low-elevation, high-velocity segment.

ANGLE OF INCIDENCE OVER THE RECORDING RANGE

It has been demonstrated above that the sonic travel path from Mauna Loa station down to Desert and Uwekahuna fits into a reasonable model for sound-wave rays moving parallel to the ground across that particular path. By contrast, the lower elevation segment of the recording range—that between Desert and Ahua—offers evidence of increased velocity which cannot be explained by temperature alone. It might be explained by a favorable component of wind velocity, but that would require wind velocities in excess of 50 mph, a condition rarely observed in Hawaii. The best situation producing such a velocity increase, as well as one which would also provide for energy focusing, would be encountered if the sonic rays impinged upon the low-elevation stations at a steeper angle of incidence.

A plausible hypothetical model is therefore considered, and with vastly oversimplified parameters. At an ambient temperature of 20° C, which is given by Blumenstock as the winter mean for the Park housing area, sonic velocity is 0.345 km/sec. In fact, we observe a velocity of 0.37 km/sec for the range south and east of the housing area. If all of this excess is assumed to be due to incidence angle, it may be computed:

$\sin \alpha = .345 = 69°$, where α is the angle between the incident ray and the vertical.

Energy from Kahoolawe can then be imagined to impinge upon the Mauna Loa and Kilauea recording range as follows: On the slopes of Mauna Loa, wave fronts move downhill and are normal to the surface of the ground; on the flatter, low-elevation terrain, wave fronts are about 20° from the vertical. Such increases in the angle of incidence would improve coupling between air and ground, and if such improvement occurs as theorized above, the maximization of available energy and "seismic" manifestations reported by residents would be the expected results.

THE GROSS PROPAGATION PATH

The many uncertainties discussed for the limited region of acoustic recording are clearly multiplied in a consideration of the size and complexity of the air space through which the energy is refracted. At present there are few concentrated data which describe atmospheric conditions over Hawaii. For example, although daily weather observations are made at Hilo, these are limited to that place and concern only operational altitudes for aircraft.

Perkins et al. (1960) illustrated many theoretical and actual instances of the focusing of sonic energy due to meteorological conditions. Their work seemed to involve more limited source-to-target distances; on their computed graphs data are restricted to areas having a maximum altitude of 10,000 ft and to lateral distances of about 100,000 ft. Variables discussed in that report were those of temperature and wind velocity; the stratification thus produced caused favorable refracting conditions and, in turn, focusing. Such conditions in Hawaii are known only generally, but salient features which would be propitious in generating the special phenomena we have recorded are summarized:

(1) Wind velocities which increase with altitude in the Hawaii direction from Kahoolawe. This condition is prevalent in the winter when trade winds (blowing westward) abate and counter trade winds blow near the ground. Thus, the propagation pattern discussed above would be enhanced during the Hawaiian winter and it would normally be inoperative during the rest of the year.

(2) High velocity (higher temperature) propagation paths which serve to refract energy in the Hawaii direction. This condition prevails most of the time (Blumenstock, 1961) in the form of a sharp temperature inversion overlying the Hawaiian area at altitudes between 5,000 and 7,000 ft.

(3) Jet streams in a sheath above 40,000 ft, the least understood, but an important, feature. These jets, which supposedly blow toward the east (thus contributing to situation (1), above), can make radical changes in direction and can attain great velocities.

Although more accurate information about possible zoning or velocity/temperature stratification between Kahoolawe and Kilauea would be helpful, it is still possible to come up with an approximation suggested by Perkins et al. (1960), who suggested a single gradient case. This oversimplification would call for Kahoolawe and Uwekahuna to lie at opposite ends of a chord connecting them. The chord, therefore, would be 190 km in length. And the circular path intersected by this chord would describe the simplified refracted energy path. If it is further assumed that tangents to this circular path at either end make an angle of 20° with the (horizontal) chord (i.e., if we interject the previously computed angle of incidence), a circular path 280 km in radius results. Such a path would reach a height of 17 km before refracting downward. This suggestion of a major refracting condition somewhere near an altitude of 55,000 ft is in good agreement with available knowledge about the altitude of the tropopause over Hawaii (described briefly in (3) above).

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